ZeV Air Showers: The View from Auger

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Abstract. In this article I briefly discuss the characteristics of the Auger observatories paying particular attention to the role of inclined showers, both in the search for high energy neutrino interactions deep in the atmosphere and as an alternative tool for the study of cosmic rays, particulartly their composition.

I INTRODUCTION

The detection of high energy showers with the radio technique has been shown to have a high potential for astroparticle physics thoroughout this conference. One of the advantages of radio detection is that provided an appropriate wavelength can be chosen, exceeding the shower dimensions, the emission from all the shower particles becomes coherent. When the emission from all particles is coherent the emitted power should scale with the square of the primary energy. The technique thus becomes most advantageous for the detection of the highest energy particles. The detection of air showers with the radio technique was started in the 1950's [1] but it experienced many difficulties and other methods took the leading role in cosmic ray detection, at first arrays of particle detectors and Čerenkov telescopes and more recently air fluorescence detectors.

One of the most intriguing questions in Astroparticle Physics concerns precisely the origin and nature of the highest energy cosmic rays. The existence of events with energy above 10^{20} eV has been known since the 1960's [2] soon after Volcano Ranch, the first large air shower array experiment, started operation. Since then they have been slowly but steadily detected by different experiments as illustrated in Fig. 1. The observation of high energy cosmic rays has been recently reviewed by Nagano and Watson [3] who have shown that there is very good agreement between different experiments including the low and high energy regions of the spectrum. By now over 17 published events above 10^{20} eV [4] and preliminary new events from HiRes [5] are enough to convince the last skeptics about the non observation of the Greisen-Zatsepin-Kuz'min (GZK) cutoff, expected because of proton interactions

with cosmic microwave photons [6]. The data suggest that the spectrum continues but little is known about the nature of the arriving particles. A large effort is being made in the 2000's to understand these particles. A new generation of large aperture experiments has started with HiRes already in operation [5], the Auger observatory in construction and with plans for using new techniques such as detection from satellites [7], with radar [8] and with radiotelescopes pointing to the moon [9] (See Fig. 1).

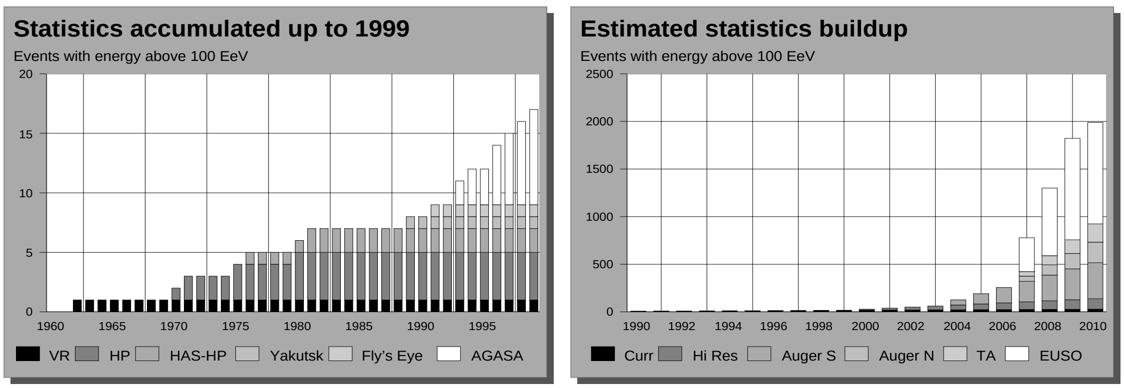

FIGURE 1. Left: Events with $E > 10^{20}$ eV detected by different experiments: Volcano Ranch (VR), Haverah Park (HP), Horizontal Air Showers in Haverah Park (HAS-HP), Yakutsk, Fly's Eye and AGASA. Right: Data buildup after 2000 from: HiRes, South and North Auger observatories (Auger S,N), Telescope Array (TA) and EUSO.

The Auger project is the last approved large aperture experiment to explore the high energy tail of the cosmic ray spectrum, those particles with energies exceeding 10^{19} eV [10]. The observatory has been shown to provide quite large acceptance for the detection of inclined showers induced by high energy neutrinos [11]. Recent analysis of inclined shower data from the Haverah Park array [12,13] has shown that it is possible to enhance the acceptance of air shower arays and to study with them the nature of the cosmic ray particles themselves [13]. In this article, after briefly addressing shower development, I will discuss the main characteristics of the Auger Observatories. The role of inclined showers for neutrino detection and composition measurements will be stressed, making reference to a model to describe the muon densties at ground level induced by inclined cosmic rays. Recent conclusions about composition at high energies using vertical and inclined showers will be reviewed.

II THE AUGER OBSERVATORIES

As a high energy cosmic ray enters and interacts in the atmosphere it gives rise to different generations of secondary particles that through succesive interactions constitute the extensive atmospheric shower. By the time the shower reaches ground level the number of particles in the shower front, mostly photons, electrons and

positrons can exceed 10^{12} for the highest energy cosmic rays. As the shower penetrates to further depths the number of photons and that of electrons and positrons follow a characteristic behavior not too far from a gaussian which reaches a maximum between 1000 and 2000 meters above sea level for vertical showers above the EeV energy scale. Muons arise mainly in the decays of charged pions produced in hadronic interactions. Unlike electrons, muons do not shower and are practically only subject to minimum ionization losses. Their depth development increases following the pions but hardly decreases after reaching its maximum. Typically only muons with energies above the GeV scale reach ground level because of decay and energy loss. At ground level the photons which are most abundant have an average energy of order 1 MeV. Electrons and muons are typically ultrarelativistic with respective average energies of order 5 MeV and 1 GeV.

In the plane transverse to shower axis the shower front has a particle density which decreases as the separation from shower axis (r) increases due to multiple elastic scattering. Photons are more numerous than electrons but the lateral distributions are similar, decreasing as $r^{-\alpha}$. Although most particles are contained within the Molière radius (of order 100 m), for showers above 1 EeV the particle density remains significant even when r exceeds one km. The muons have a significantly flatter lateral distribution. Although they are outnumbered by electrons, the muon density can dominate at large r (in the km scale). The shower front develops a characteristic curvature depending on the position of shower maximum. The thickness of the shower front is mostly governed by the different delays that the particles accumulate as they deviate from the shower axis. Higher energy particles tend to deviate less and thus arrive earlier.

Extensive air showers have similar distributions whatever the nature of the initial particle. The establishment of composition is one of the toughest challenges in the detection of high energy cosmic rays. Simulations reveal some differences that can be used for this purpose. One of them is the total number of muons in a shower relative to electrons. Showers induced by photons mainly cascade into electrons and photons and only ocasionally a photon photoproduces mostly pions, channelling part of its energy into a hadronic shubshower. As a result showers induced by photons typically have of order ten times fewer muons than showers induced by protons of the same energy. If the cosmic rays are hadrons, the number of muons serves as a discriminator between heavy and light nuclei, the former having a somewhat higher muon content.

The Auger project is conceived as two 3,000 km^2 twin observatories in the northern and southern hemispheres, situated at mid latitudes. Each observatory is a hybrid experiment combining the two only succesful techniques for the study of EeV cosmic rays up to now, namely an array of particle detectors and a fluorescent detector (see Fig. 2). The *Engineering Array* is now being constructed in *Pampa Amarilla* in Mendoza, Argentina. It is a fraction of the Southern Auger array covering only 55 km^2 and which should be finished during the year 2001. The first physics results could be coming very soon. The Northern observatory is planned to be sited in Utah, U.S.A.

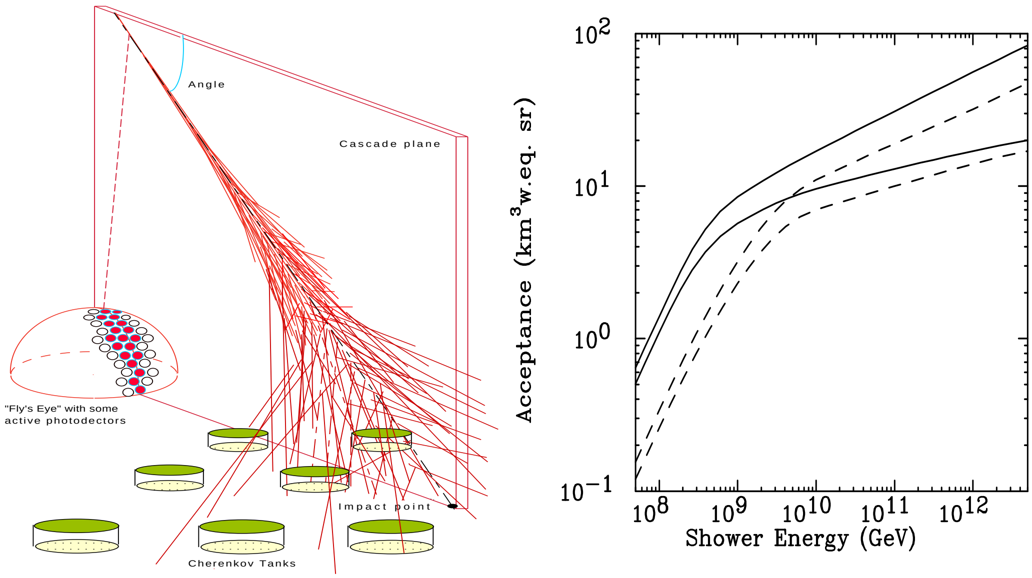

FIGURE 2. Left: Shower detected by tanks and by a Fluorescent light detector or "eye". Right: The full (dashed) line is the acceptance of the Auger Array for detecting the electrons and photons produced in hadronic (electromagnetic) showers of $\theta > 60°$. Lower curves refer to showers wih axis falling on the array.

The ground array uses cylindrical water Čerenkov detectors of 10 m^2 surface area and 1.2 m of height, each instrumented with three photodetectors. They are going to be arranged in a hexagonal grid separated 1.5 km from each other and extending over a surface area of 3,000 km^2. Two such tanks have been running in coincidence with the AGASA array. When electrons and photons reach the tank they are typically absorbed and they give a Čerenkov light signal which is proportional to the total energy carried by them. On the other hand most muons travel through the whole tank and give a light signal that is proportional to their track length within the tank. The arrival directions of the incident cosmic rays is determined from the arrival times of the shower front, typically with one degree accuracy. Each of the tanks is powered with a solar cell and the data are transmitted from the detectors to a central station by conventional wireless communication technology. Final triggering will be made at the central station.

The relative contributions of each particle species to the tank signals are comparable for a proton initiated shower because the average energies carried by photons, electrons and muons partly compensate the diferences in particle density. As we approach shower core both the relative number of muons and the time spread of the signal become smaller. At distances of order 1.5 km however the signals in the tanks can spread over times of order 2 μs. At large distances to shower axis the relative signal induced by muons becomes larger than that of electrons and photons. As the signal will be digitized with few nanosecond timing, the identification of large Čerenkov spikes from the individual muons will allow their separation, particularly well away from the shower core.

The particle density and the arrival times serve for the determination of the shower energy and its direction. The ground array has a large aperture, a 100% duty cycle and a uniform right ascension exposure for the study of anisotropy. The shower energy determination is usually determined by the particle density at a given distance to shower axis. Although this distance is chosen to minimize the effects of fluctuations and different primaries, the results are unavoidably dependent to some extent on both the nature of the arriving particle and the interaction model used for shower simulation.

As the shower develops in the atmosphere, nitrogen is excited and emits fluorescence photons in proportion to the number of ionizing particles, a few photons per meter of ionizing track length. By measuring the light signal and its arrival time from different positions along the shower depth development it is possible to detect and study very high energy cosmic rays. The fluorescence technique requires mirrors with imaging capabilities and covering a sufficient field of view to capture the depth development of the shower. The arrival direction of the cosmic ray particle is determined by the geometry and timing of the arriving light. This method has been very succesful at detecting EeV cosmic rays in dark nights.

The fluorescence detector in the Southern observatory will consist on four "eyes", three near the perimeter of the surface array and one roughly in the central part, at locations which are slightly elevated with respect to the rest of the detector. These eyes are located to monitor the atmosphere on top of the ground array. In the current design each eye is based on Schmidt optics and consists of mirror modules each with a 1.7 m diaphragm preceeding a 7 m diameter mirror and limiting the field of view of each mirror to approximately a $30^\circ \times 30^\circ$ fraction of the sky [14]. Each eye views 30° upwards from the horizon and combines several of these mirror modules in the azimuthal directions. The central eye requires 12 modules to cover 360° in azimuth and the other three eyes to be sited on the perimeter of the ground array only require 6 or 7 to cover 180° or 210° in azimuth [15]. The focal plane of each mirror is instrumented with a camera, an array of 20×22 optical modules, each of viewing aproximately $1.5^\circ \times 1.5^\circ$.

The detection of 10^{20} eV showers with the fluorescence technique necessarily requires the collection of light which is produced over 20 km away and thus subject to significant dispersion and attenuation in the atmosphere. Moreover the conversion of light to shower signal is affected by uncertainties in the geometrical reconstruction of the shower direction. Much of the geometrical uncertainty in the reconstruction is eliminated if the showers are detected from two or more eyes, that is from at least two different locations. This is the *stereo viewing* which constitutes one of the important advantages of HiRes [5]. In the Auger observatory many of the showers will be viewed in stereo and even by three eyes.

The fluorescence detector measures the particle production as a function of depth into the atmosphere and it is therefore a calorimetric energy determination. The uncertainty in the energy determination is therefore reduced with respect to a particle array which is measuring the particle content at a particular point in shower development and thus is subject to fluctuations between different showers. The

ability to follow the depth development of the shower is also an important advantage because shower maximum can be determined directly. Such measurements of depth of maximum are most important for the establishment of primary composition.

The Auger observatory will be the first hybrid detector combining the fluorescence technique with a ground array for the detection of EeV cosmic rays. The combination of the two techniques is an improtant step because besides adding all the features of the two techniques, it will serve for cross calibration. The angular resolution of the fluorescence technique improves when used in combination with the ground array, because much of the geometrical uncertainty in the reconstruction of the shower profile is eliminated when the impact point of the shower axis is determined by the ground array. The power for composition of using both the method of establishing the depth of maximum and that of measuring muon content will help to eliminate part of the ambiguity associated to the interdependence between composition and interaction models.

III INCLINED SHOWERS AND COMPOSITION

The fact that high energy particles exceeding the GZK cutoff have been observed allows one to make a strong case for the existence of high energy neutrinos. Although the origin and nature of these particles is unknown it is difficult to conceive the observed flux of any particle species without the existence of a flux of high energy neutrinos. The detection of inclined showers has been for long known to be a possible way to detect very high energy neutrinos interacting in the atmosphere [16]. When a neutrino interaction happens deep into the atmosphere, the showe can reach its maximum very close to ground level in spite of being close to horizontal. Such a shower would look much like an ordinary vertical shower with high electron and photon content and a front curvature corresponding to shower maximum near ground level. The Auger observatory will be sensitive to high energy neutrinos. Its acceptance for the electromagnetic component of deep and inclined showers induced by neutrinos exceeds 10 km^{3}sr of water equivalent [11] (See Fig. 2).

The original motivation for the study of inclined showers induced by cosmic rays was to understand the background of cosmic ray signals to neutrino detection, but these showers have proved to be of great interest on their own. The study of cosmic ray showers by particle arrays has been mostly restricted to relatively vertical showers, typically resticting zenith angles to less than 45°. The particle densities in such such showers keep the characteristic circular symmetry allowing an easy reconstruction of the event energy by measuring it at a given distance to the shower axis. The acceptance $\mathcal{A}$ of a ground array of area A for cosmic rays depends on θ_{max}, the maximum zenith angle that the array can detect:

$$\mathcal{A} = \int A \cos\theta \; d(\sin\theta) \; d\phi = \pi A[1 - \cos^2\theta_{max}] \tag{1}$$

If only zenith angles below $\theta_{max} = 45°$ are analysed with the Auger observatory, its acceptance would be 4,500 km^{2}sr. The acceptance of the observatory will double

if the analysis of showers can extend to zenith angles less than 90°. It has recently become quite clear that inclined showers produced by cosmic rays can be analysed at least with arrays of water Čerenkov tanks [17,12,13]. Moreover the analysis of these showers has also shown to have a remarkable potential for the study of primary composition [13].

Much development has been possible by separately modelling the distortion of the muon density patterns in inclined showers under the influence of the Earth's magnetic field [17]. The showers can first be studied in the absence of a magnetic field where two important facts emerge for inclined showers: a) Most of the muons are produced in a well defined region of shower development which is quite distant from the ground and b) the lateral deviation of a muon is inversely correlated with its energy. Most of the characteristics of the muon densities in inclined showers are governed by the distance and depth travelled by the muons which is of order 4 km for vertical showers, becomes 16 km at 60° and continues to rise as the zenith angle rises to exceed 300 km for a completely horizontal shower. This distance determines the minimum energy needed for a muon to reach ground level and thus fixes the average energy of these muons that can be of a few hudred GeV.

In the absence of a magnetic field we can assume that all muons are produced at a given altitude d with a fixed transverse momentum $p_\perp$ that is uniquely reponsible for the muon deviation from shower axis. In the plane transverse to shower axis at ground level (transverse plane) the muon deviation, $\bar{r}$, is inversely related to muon momentum p. The density pattern has full circular symmetry. When the magnetic field effects are considered the muons deviate a further distance δx in the perpendicular direction to the magnetic field projected onto the transverse plane $\vec{B}_\perp$, given by:

$$\delta x = \frac{e|B_\perp| d^2}{2p} = \frac{0.15 |B_\perp| d}{p_\perp} \, \bar{r} = \alpha \, \bar{r}, \tag{2}$$

where in the last equation $B_\perp$ is to be expressed in Tesla, d in m and $p_\perp$ in GeV.

Eq. 2 is telling us that all positive (negative) muons that in the absence of a magnetic field would fall in a circle of radius $\bar{r}$ around shower axis, are translated a distance δx to the right (left) of the $\vec{B}_\perp$ direction. As the muon deviations are small compared to d they can be added as vectors in the transverse plane and the muon density pattern is a relatively simple transform of the circularly symmetry pattern. The dimensionless parameter α measures the relative effect of the translation. For small zenith angles d is relatively small and $\alpha << 1$ so that the magnetic effects are also small, and results into slight elliptical shape of the isodensity curves. For high zeniths however $\alpha > 1$ the magnetic translation exceeds the deviation the muons have due to their $p_\perp$ and *shadow* regions with no muons appear as confirmed by simulation. For an approximate $p_\perp \sim 200$ MeV and $B_\perp = 40\ \mu$T this happens when d exceeds a distance of order 30 km, that is for zeniths above $\sim 70°$. The muon patterns in the transverse plane can be projected onto the ground plane to compare with data as well as standard simulation programs. Realistic density patterns are

obtained if these ideas are modified accounting for the energy distributions of the muons at a given $\bar{r}$. In the simulations it is the average muon energy which is inversely related to $\bar{r}$.

For each zenith angle the shape of the lateral distribution of the muons does not change for showers of energy spaning over four orders of magnitude. Different primary particles and interaction models also have similar distribution functions in shape. As a result one only needs the total number of muons to describe a shower of given zenith. This normalization scales with the proton energy E as:

$$N = N_{ref}\ E^{\beta} \tag{3}$$

where β and N_{ref} are slightly model dependent constants [12].

The inclined shower data obtained in the Haverah Park array was analysed with the help of the model described above. The Haverah Park detector was a 12 km^2 air shower array using 1.2 m deep water Čerenkov tanks that was running from 1974 until 1987 in Northern England which has been described elsewhere [18]. It is the array that has been made closest to the ground array of the Auger observatory because it also consisted on water Čerenkov tanks Particular care was taken to account for new corrections to the tank signals that arise when horizontal events are detected. These include light that falls directly into the photoubes, enhanced delta ray signal because muons are more energetic, catastrophic energy losses for the muons and a signal due to electromagnetic particles from muon decay.

The event rate as a function of zenith angle has been simulated using the modelled muon distributions. The qualitative behaviour of the registered rate is well described in the simulation and the normalization is also shown to agree with data to better than 30% using the measured cosmic ray spectrum for vertical incidence, assuming proton primaries and using the QGSM model [12]. More impressive are the results of fits of the models for muon densities to the observed particle densities sampled by the different detectors on an event by event basis. This result demonstrates that the acceptance of these detectors can be extended to practically all zenith angles. The analysis of the nearly 10,000 events recorded with zenith angles above 60° is a complex process that involves a sequence of time fits to get the arrival directions and density fits to obtain the energy under the assumption that the primaries are protons. The curvature of the shower front is considered and care is taken to account for the correlations between the shower energy and the impact point of the shower.

The analysed data are subject to a set of quality cuts: the shower is contained in the detector (distance to core less than 2 km), the χ^2 probability of the event is greater than 1% and the downward error in the reconstructed energy is less than 50%. These cuts ensure that the events are correctly reconstructed and exclude all events detected above 80°. Examples of reconstructed events compared to predictions are illustrated in Fig. 3. Two new events with energy exceeding 10^{20} eV have been revealed. The results have been compared to a simulation that reproduces the same fitting procedure and cuts using the cosmic ray spectrum deduced from vertical air shower measurements in reference [3]. The agreement between the integral

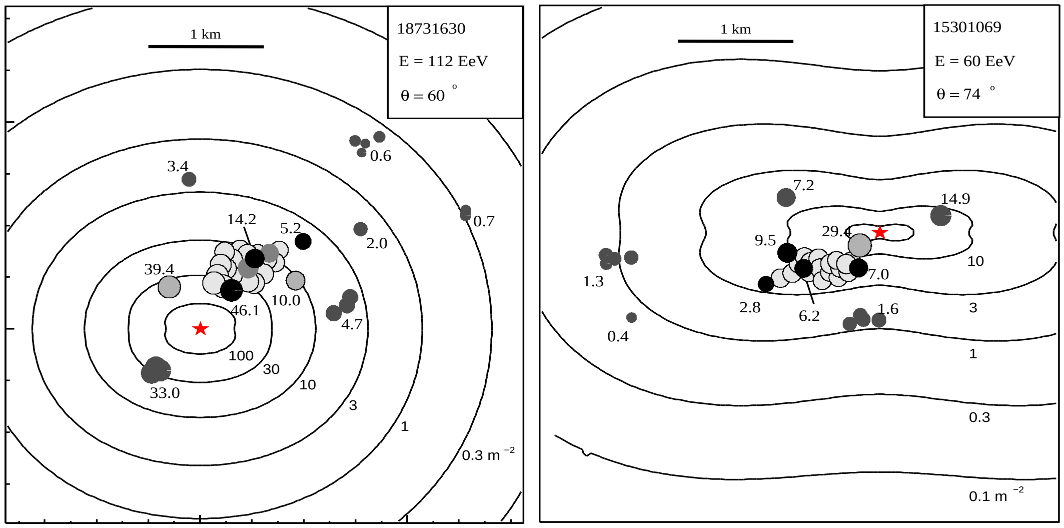

FIGURE 3. Density maps of two events in the plane perpendicular to the shower axis. Recorded muon densities are shown as circles with radius proportional to the logarithm of the density. The detector areas are indicated by shading; the area increases from white to black as 1, 2.3, 9, 13, 34 m^2. The position of the best-fit core is indicated by a star. Selected densities are also marked. The y-axis is aligned with the component of the magnetic field perpendicular to the shower axis.

rate above 10^{19} eV measured and that obtained with simulation is striking when the QGSJET model is used for the interactions. Sibyll leads to a slight underestimate [13].

The universality of the muon lateral distribution function is very powerful and once the equivalent proton energy is determined for all events, corresponding energies can be easily obtained for different assumptions about primary composition. In the case the incoming particles are iron nuclei (photons), the primary energy can be calculated multiplying the equivalent proton energy by a factor which is ~ 0.7 (6) for 10^{19} eV and varies slowly as the primary energy raises. As a result when a photon primary spectrum is assumed, the simulated rate seriously underestimates the observed data by a factor between 10 and 20. A fairly robust bound on the photon composition at ultra high energies can be established assuming a two component proton photon scenario. The photon component of the integral spectrum above 10^{19} eV (4×10^{19} eV) must be less than 41% (65%) at the 95% confidence level. Details of the analysis are presented in [13] and will be expanded elsewhere.

IV SUMMARY

The Auger detector will soon give an important contribution to the observation of the high energy tail of the cosmic ray spectrum. Its acceptance is close to 9,000 km^2sr when considering the inclined air showers. Its hybrid character will be of great value to cross calibrate the two classes of detectors and for establishing

the composition. The combined analysis of vertical and horizontal showers will also set important limits to composition at high energies. The combination of two different techniques for composition studies will be of great importance in reducing the uncertainties associated to the hadronic interaction models.

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